Twin-jet and trijet aircraft: a study for an optimal design of regional aircraft

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ABSTRACT

Aircraft with three engines, as known as trijet, became a standard design among manufacturers after 1964 when the FAA's 60-minute rule was established for these aircraft. This regulation restricted the flight path to 60 minutes' flying time to a suitable airport, therefore affecting the operation costs and limiting the range of twin-jet aircraft. However, improvements to the engine's reliability in the following decades allowed ETOPS certification for twin-jet aircraft. The traditional trijet designs were slowly retired, the last commercial trijet flight was in 2014.The industry abandoned the trijet design as solution for commercial aviation; however, executive jets such as the Falcon 7x and Falcon 8x, certified in 2016, show that this configuration might still be advantageous for specific markets. The certification at one engine inoperative condition presents advantage for trijet aircraft reducing take-off thrust, since when one engine is inoperative, 75% of the installed thrust is available for the trijet aircraft, while this value is only 50% for a twin-jet aircraft. An initial study conducted showed a trend of lower thrust to weight ratio for trijet aircraft when compared to twin-jet aircraft, being particularly evident for MTOW (maximum take-off weight) lower than 75,000 lb. The aim of this work is to study the viability of a trijet aircraft configuration and potential advantages for a regional aviation scenario. The trijet configuration performance was evaluated and compared to twin-jet configuration in a multidisciplinary design environment considering disciplines such as aerodynamics, noise, performance, flight mechanic, weight, and structure. An aircraft with MTOW of 48,500 lb was studied and the results show that a reduction up to 9.4% of installed thrust might be achieved with the trijet design compared to twin-jet aircraft when the balanced field length is the critical constraint. However, flyover noise and structural weight might increase slightly in trijet design.

KEYWORDS: trijet; balanced field lenght; multidisciplinary design; installed thrust reduction

NOMENCLATURE

Latin
A - Area
BFL - Balanced field length
C_d - Drag coefficient
C_f - Turbulent or laminar skin friction coefficient
C_L - Lift coefficient
D – Drag
D_2 - Drag at V_2
EPNL - Effective perceived noise level
FF - Form factor
F - Thrust or aerodynamic force
g - Acceleration due to gravity
h - Obstacle height
IF - Interference factor
K – Dimensionless equation factor
K_d - 1 for curved duct cross section
K_m - 1 for design Mach below 1.4 and 1.5 for design Mach above 1.4
K_{fsp} - fuel density [$\frac{lb}{gal}$]
L - Lift or Length
L_{nlc} - Nacelle length from inlet lip to compressor face [ft]
M - Momentum or Mach number at operational conditions under investigation
MTOW - Maximum take-off weight
N_e - Number of engines for twin-jet or trijet
N_{inl} - Number of inlets for twin-jet or trijet configuration
N_{tnk} - Number of separate fuel tanks
PNL - Perceived noise level
P_2 - Maximum static pressure at engine compressor face [psi]
q - Dynamic pressure
Re - Reynolds number, based on component characteristic length
S - Area
T - Thrust
V - Speed
y_{eng} - Distance between aircraft center of gravity and thrust force
W – Weight
W_e - Engine dry weight for twin-jet or trijet [lb]

Greek
γ - Climb gradient
ΔS - Inertia distance
ρ - Air density
Subscripts
ai – Air induction duct
d – Duct
e – Engine
fsl – Fuel system
fl – Mission fuel
fus - Fuselage
inl – Engine inlet
min – Minimum
ncl – Nacelle
OEI – One engine inoperative
prp – Propulsion control system
ref – Wing reference
r% - Installed thrust reduction for trijet considering baseline twin-jet
to – Take-off
tri – Trijet aircraft
twin – Twin-jet aircraft
vt – Vertical tail
wet - Component wetted area
2 – Condition at Takeoff safety speed which must be attained at the 35 ft height

1 INTRODUCTION

The three-engine aircraft configuration for commercial aviation became widespread among manufacturers after 1964 when FAA 14 CFR § 121.161 regulation was modified, exempting trijet airplanes from operating at a maximum 60-minute flying time of an adequate airport. This regulation was applied to both two- and three-engine airplanes since 1953 and most transoceanic flights were operated in a four-engine aircraft. However, improvements to the engine's reliability in the following decades lead to a change in the regulation, allowing ETOPS (Extended-range Twin-engine Operational Performance Standards) certification for twin-jet aircraft. The traditional trijet designs, such as DC-10, Boeing 727, and L-1011 were slowly retired, the MD-11 performed the last commercial trijet flight in 2014.The industry abandoned the trijet design as solution for commercial aviation; however, executive jets such as the Falcon 7x and Falcon 8x, certified in 2016, show that this configuration might still be advantageous for specific markets, Table 1 shows some commercial and business trijet throughout history. Also, a patent filed by Airbus in 2006 [1] describes a new trijet aircraft configuration, demonstrating that still this design may have some benefits not yet explored by the aerospace industry.

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Table 1: Commercial and business trijet throughout history

Aircraft	First Flight	Introduction	Role
Falcon 8x	2015	2016	Business jet
Falcon 7x	2005	2007	Business jet
MD 11	1990	1990	Wide-body jet airliner
Falcon 900	1984	1986	Business jet
Yak-42	1975	1980	Narrow-body jet airliner
Tu-154	1968	1972	Narrow-body jet airliner
L-1011	1970	1972	Wide-body jet airliner
DC-10	1970	1971	Wide-body jet airliner
Yak-40	1966	1968	Regional jet
727-200	1963	1964	Narrow-body jet airliner

The certification at one engine inoperative condition presents advantage for trijet aircraft reducing take-off thrust, since when one engine is inoperative, 75% of the installed thrust is available for the trijet aircraft, while this value is only 50% for a twin-jet aircraft. An initial study was conducted involving 30 aircraft, showing a trend of lower thrust to weight ratio for trijet aircraft when compared to twin-jet aircraft. This is particularly evident for MTOW (maximum take-off weight) lower than 75,000 lb as illustrated in Fig. 1, this initial study showed that trijet aircraft have an average of 19% lower installed thrust than twin-jets with the similar MTOW. The aircraft design is related to a multidisciplinary view. So, the thrust reduction and the implementation of a third engine have impacts on fuel burn, structural weight, external noise, performance, certification, maintenance, and the fuel feed system. In this sense, the multidisciplinary view justifies distinct thrust to weight ratio reduction caused by trijet configuration for different MTOW range.

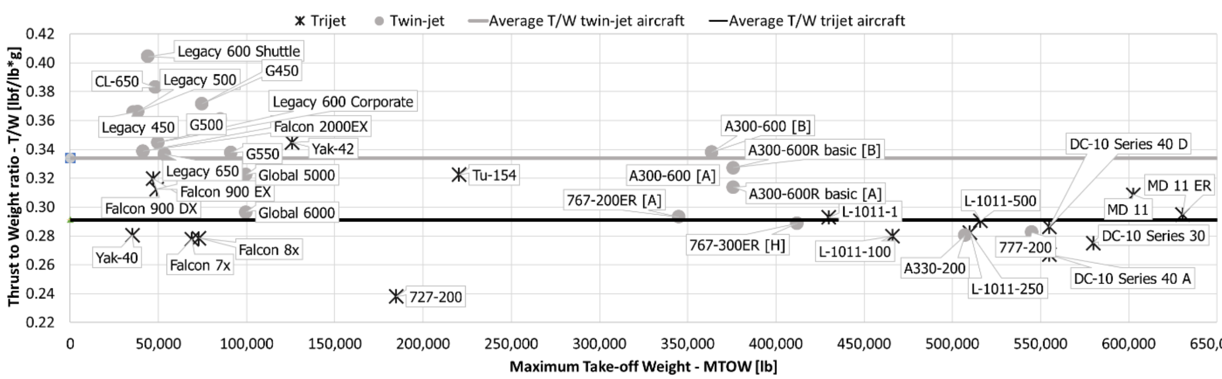

Figure 1: Thrust to weight ratio vs MTOW (Maximum Take-off Weight) for twin-jet and trijet aircraft

The aim of this work was to study the viability of a trijet aircraft configuration and potential advantages for a regional aviation scenario. The trijet configuration performance will be evaluated and compared to twin-jet configuration in a multidisciplinary design environment considering disciplines such as aerodynamics, noise, performance, flight mechanic, weight, and structure. The multidisciplinary balance of these variables for an aircraft with MTOW of 48,500 lb is shown in this paper. The parameters considered are drag of the nacelles, vertical tail, thrust and structural weight. The determination of these parameters was constrained by requirements of flyover noise, balanced field length and minimum climb gradient of a baseline twin-jet aircraft.

2 EVALUATION METHODOLOGY

The trijet configuration will be analyzed considering as baseline a twin-jet aircraft with maximum take-off weight of 48,500 lb and cruise Mach number of 0.75. The main geometric and performance characteristics of the baseline twin-jet aircraft are shown in Table 2.

Table 2 – Main geometric and performance characteristics of the twin-jet aircraft used as baseline.

Aircraft	MTOW [lb]	48,500
Wing	Area [m^2]	51.2
	Span [m]	8.8
	1/4 Chord Sweep [º]	22.73
Vertical Tail	Area [m^2]	7.2
	Height [m]	3.1
	1/4 Chord Sweep [º]	10
Horizontal Tail	Area [m^2]	11.2
	Span [m]	7.6
	1/4 Chord Sweep [º]	17
Fuselage	Length [m]	27.93
	Width [m]	2.28
	Height [m]	2.28
Performance	Cruise Mach Number	0.75
	Service Ceiling [ft]	37,000
	FAR take-off field length, Sea level ISA + 0°C [m]	2400
Propulsion	Max. take-off thrust at sea level [lb]	15,160
	Turbofan bypass ratio	4.5
	Thrust to weight ratio - T/W [lbf/lb*g]	0.312

The three-engine version will have its extra engine installed inside the aft fuselage with a serpentine air induction system, commonly known as s-duct, over the fuselage. The three-dimensional model can be seen in Fig. 2.

Figure 2: Twin-jet and trijet configuration

The first step in the analysis is to determine the thrust to weight ratio (T/W) required for the trijet configuration to obtain the main performance characteristics established. The thrust will be determined considering that the balanced field length (BFL) for both aircrafts must be the same. In the event of one engine inoperative the three-engine version will have 75% of its installed thrust available, while the twin-jet aircraft will have only 50% of its installed thrust.
The second discipline involved in the analysis is the noise produced by the aircraft, there are three categories of certificated noise: side-line, flyover, and approach noise. The side-line noise is measured in

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the take-off lane and the main contribution is the installed thrust of the aircraft, as the trijet will have a lower T/W, it is expected that the side-line noise will be lower for the trijet. The flyover noise is measured between the brakes off location and a point 5000 m after brakes off. The maximum climbing gradient of the trijet aircraft will be lower since it will have less installed thrust and therefore the aircraft will be closer the microphone on the ground. The main contribution for the approach noise is the airframe, since both aircrafts share basically the same airframe, this noise will likely to be same.
The third aspect utilized to check the minimum T/W for the three-jet configuration is the minimum climbing gradient, this requirement depends on the number of engines as shown in Table 3 [2].

Table 3 - FAR 25 Climb gradient requirements for aircraft with 2 engines and 3 engines (N_e = number of engines).

Phase of flight	**Airplane configuration**				**Climb Gradient %**	
	Flaps	**Undercarriage**	**Engine Rating**	**Flight speed**	**N_e = 2**	**N_e = 3**
Lift-off 1st segment	Take-off	Down	Take-off	V_{lof} Ÿ V_2	0	0.3
Take-off 2nd segment	Take-off	Up	OEI Take-off	$V_2 \geq 1.20\ V_s$	2.4	2.7
Path Final segment	Up	Up	Max. Cruise	$V \geq 1.2\ V_s$	1.2	1.5
Approach climb	Approach	Up	Take-off	$V \leq 1.5\ V_s$	2.1	2.4
Landing climb	Landing	Down	Take-off	$V \leq 1.3\ V_s$	3.2	3.2

The thrust determined in the previous steps is then used to calculate the powerplant weight of the trijet configuration, which includes nacelle, pylon, engine, fuel, propulsion and air induction system weight. A class II weight estimation method is used in these calculations. The nacelle sizing is particularly important since the third nacelle will add drag for the trijet aircraft.
The trijet configuration indicates a potential reduction in vertical tail area, since there is less asymmetric thrust in the case of one engine inoperative. Therefore, the vertical tail must be checked and if the dimensioning criteria is for OEI, cross-wind landing, or Dutch-roll.
The steps described previously are iterated to check if the performance requirements of BFL, noise and minimum climbing gradient are still being met, this workflow is summarized in Fig. 3.

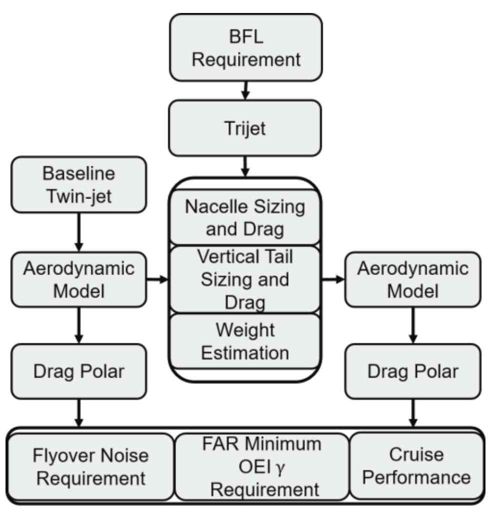

Figure 3: Twin-jet to trijet configuration workflow

3 RESULTS AND DISCUSSION

3.1. Balanced field length requirement.

The balance field length requirement was estimated using Eq. (1, based on theoretical and statistical data [3].

$$BFL = \frac{0.863}{1+2.3\Delta\gamma_2}\left(\frac{\frac{W_{to}}{S}}{\rho\, g\, C_{L2}} + h_{to}\right)\left(2.7 + \frac{1}{\frac{\overline{T}}{W_{to}} - \mu'}\right) + \frac{\Delta S_{to}}{\sqrt{\sigma}} \quad (1)$$

Where

C_{L2} - Lift coefficient at V_2=1.11

g - Acceleration due to gravity

h_{to} - Obstacle height=10.7 m

S - Reference wing area =51.2 m^2

W_{to} - Take-off weight in N=215.8 kN for twin-jet

T_{to} - Maximum static thrust=67.4 kN for twin-jet

$\overline{T}$ - Average thrust in take-off run= $0.75T_{to}\left(\frac{5+\text{bypass ratio}}{4+\text{bypass ratio}}\right)$

ρ - Air density=1.225 $\frac{kg}{m^3}$

$\mu' = 0.01C_{Lmax}+0.02=0.036$

ΔS_{to} - Inertia distance= 200 m

$\Delta\gamma_2 = \gamma_2 - \gamma_{2min}$

$\gamma_2 = \sin^{-1}\left(\frac{T_{OEI}-D_2}{W_{to}}\right)$

T_{OEI} - Thrust for one engine inoperative

$\gamma_{2min} =$ 0.024 for 2 engines and 0.027 for 3 engines

D_2 - drag at V_2 =16,6 kN for twin-jet and 16,7 kN for trijet

Solving the above equation iteratively, using the workflow shown in Fig. 3 and not considering the flyover noise requirement, it can be show that the maximum static thrust can be 9.4 % lower or 61.1 kN.

3.2. Flyover noise requirement

The flyover noise was estimated considering a model that the noise perceived by the microphone decays with the logarithm of the distance the source [4]. In this model, the trajectory of the aircraft is calculated considering engines at maximum rating and the microphone is at 5000 from the start of the take-off. Considering 9.4% installed thrust reduction from the twin-jet design, the effective perceived noise level (EPNL) is 1.2 dB larger for the trijet configuration as shown in Fig. 4.This result was expected since the trijet has a trajectory closer to the microphone when compared with the twin-jet configuration.

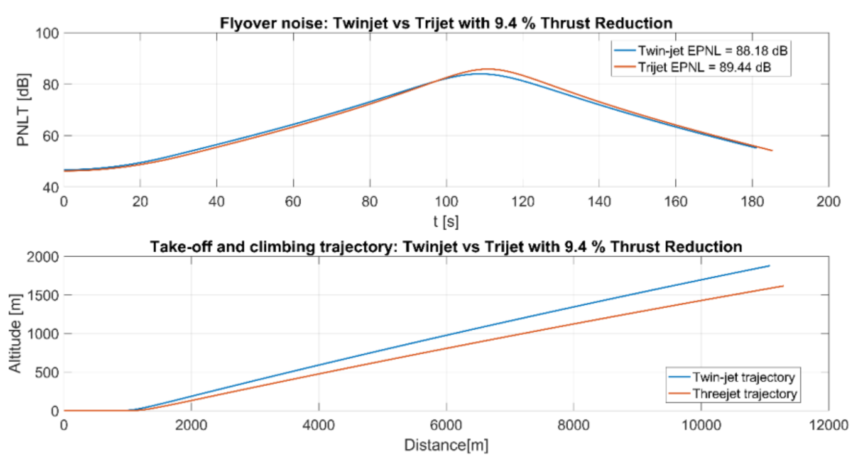

Figure 4: Flyover noise comparison between twin-jet and trijet configuration with 9.4% installed thrust reduction

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3.3. Minimum climb gradient

The climb gradient can be estimated by Eq. 2, assuming that the aircraft is at constant speed.

$$sin(\gamma) = \frac{T}{W} - \frac{D}{L} \qquad (2)$$

Eq. 3 to Eq. 4 shows the procedure to calculate the theoretical thrust reduction possible for the trijet configuration.

$$sin\left(\gamma_{min_{twin}}\right) = \left(\frac{T}{W}\cdot\frac{1}{2}\right)_{twin\ OEI} - \left(\frac{D}{L}\right)_{twin}$$
$$sin\left(\gamma_{min_{tri}}\right) = \left(\frac{T}{W}\cdot\frac{2}{3}\right)_{tri\ OEI} - \left(\frac{D}{L}\right)_{tri} \qquad (3)$$

$$t_{r\%} = 1 - \frac{\left(\frac{T}{W}\right)_{twin}}{\left(\frac{T}{W}\right)_{tri}} \qquad (4)$$

Considering the first flight segment, which has $\gamma_{min_{twin}}$ =2.4% and $\gamma_{min_{twin}}$ =2.7% at one engine inoperative condition, it can be shown that for the aircraft studied in this paper $t_{r\%}$=22.3%. This value is greater than the 9.4% estimated for the BFL requirement, showing that the climb gradient requirement is not the dimensioning parameter for determining thrust to weight ratio.

3.4. Weight estimation

The weight was estimated using class II methods from General Dynamics and Torenbeek [5]. The power plant weight was divided in 4 categories: 1) Nacelles and pylons, 2) Air induction system, 3) Propulsion system and 4) Fuel System. These equations depend on the number of engines, thrust of each engine, air inlet diameter, fuselage length and fuel volume. Considering, 9.4% thrust reduction the trijet configuration has a weight increase of 780 lb (1.6% of the original MTOW) as show in Fig. 5.

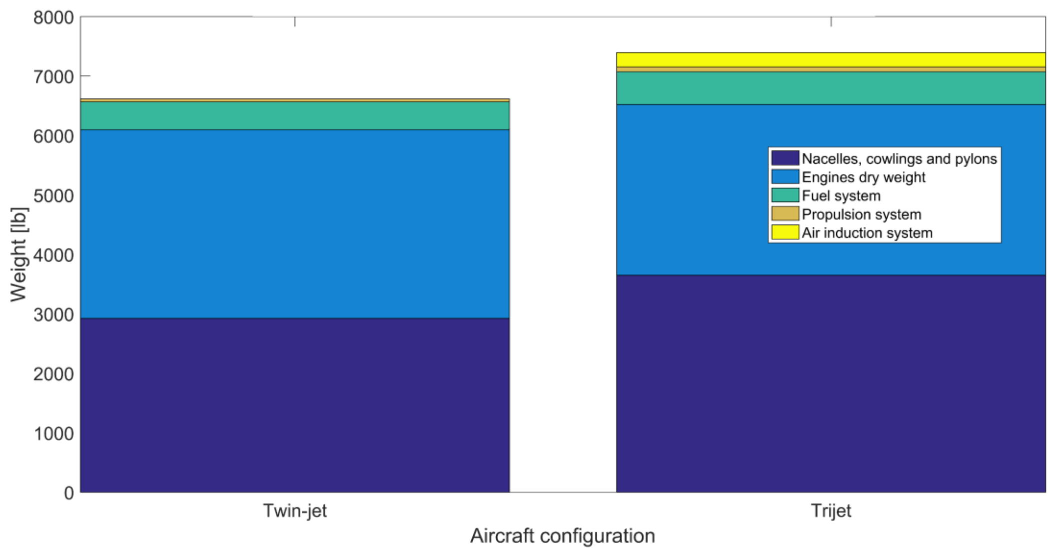

Figure 5: Power plant weight difference between trijet and twin-jet aircraft with 9.4% thrust reduction: 780 lb(1.6% of baseline MTOW)

Nacelle weight is assumed to consist of the structural weight associated with pylon and the engine external ducts or cowls for podded engines. For buried engine, as the one in the trijet design, the nacelle weight consist of the structural weight associated with special cowling, ducting provisions (other than the inlet duct which is included in air induction system) and any special engine mounting provisions. Eq. 5 and 6 show the GD nacelle weight estimation method utilized [5]:

$$W_{ncl_{twin}}=7.435N_{in_{twin}}(A_{inl_{twin}}{}^{0.5}L_{ncl}P_2)^{0.731} \tag{5}$$

$$W_{ncl_{tri}}=7.435N_{in_{tri}}(A_{inl_{tri}}{}^{0.5}L_{ncl}P_2)^{0.731} \tag{6}$$

The air induction duct for the third engine in the trijet configuration was estimated using Eq. 7. This result was only used for the trijet configuration since it has the S-duct inlet.

$$W_{ai_{tri}}=0.32N_{inl_{tri}}L_dA_{inl_{tri}}{}^{0.65}P_2{}^{0.6}+1.731(L_dN_{inl_{tri}}A_{inl_{tri}}{}^{0.5}P_2K_dK_m)^{0.7331} \tag{7}$$

The propulsion control weight consists of engine controls and engine starting system. The same equation was applied to estimate the engine controls weight for both aircraft designs. However, the engine starting system weight for the trijet configuration utilized a relationship for two and four engines and therefore an average value was taken in the computations. Eq. 8 and Eq. (9 show the GD weight estimation method utilized.

$$W_{prp_{twin}}=0.686(L_{fus}N_{e_{twin}})^{0.792}+9.33\left(\frac{We_{twin}}{1000}\right)^{1.078} \tag{8}$$

$$W_{prp_{tri}}=0.686(L_{fus}N_{e_{tri}})^{0.792}+\left(9.33\left(\frac{We_{tri}}{1000}\right)^{1.078}+49.19\left(\frac{We_{tri}}{1000}\right)^{1.078}\right)\frac{1}{2} \tag{9}$$

The fuel system weight was estimated based on Torenbeek relationships for integral fuel tanks as shown in Eq. 10 and Eq. 11.

$$W_{fls_{twin}}=80\left(N_{e_{twin}}+N_{tnk}-1\right)+15N_{tnk}{}^{0.5}\left(\frac{W_{fl}}{K_{fsf}}\right)^{0.33} \tag{10}$$

$$W_{fls_{tri}}=80\left(N_{e_{tri}}+N_{tnk}-1\right)+15N_{tnk}{}^{0.5}\left(\frac{W_{fl}}{K_{fsf}}\right)^{0.33} \tag{11}$$

The total power plant weight for both aircraft can be given by Eq. 12 and Eq. 13. The numeric value of the parameters of this weight estimation are show in Table 4.

$$W_{pwr\_ncl_{twin}}=W_{e_{twin}}+W_{ncl_{twin}}+W_{prp_{twin}}+W_{fls_{twin}} \tag{12}$$

$$W_{pwr\_ncl_{tri}}=W_{e_{tri}}+W_{ncl_{tri}}+W_{prp_{tri}}+W_{fls_{tri}}+W_{ai_{tri}} \tag{13}$$

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Table 4 - Weight estimation parameters

Parameter	Value
$N_{in_{twin}}$ or $N_{e_{twin}}$ [-]	2
$N_{in_{tri}}$ or $N_{e_{tri}}$ [-]	3
$A_{inl_{twin}}$ [ft^2]	19.02
$A_{inl_{tri}}$ [ft^2]	11.49
L_{ncl} [ft]	13.12
L_d [ft]	6.56
P_2 [psi]	24
K_d [-]	1
K_m [-]	1
L_{fus} [ft]	27.93
N_{tnk} [-]	2
W_{fl} [lb]	8735.6
K_{fsf} [lb/gal]	6.426
$W_{e_{twin}}$ [lb]	3172
$W_{e_{tri}}$ [lb]	2873.8

3.5. Vertical tail sizing and drag

The vertical tail size for trijet configuration was estimated considering that its dimensioning condition was at one engine inoperative. Fig. 6 shows the main forces acting on the aircraft when the left engine is inoperative.

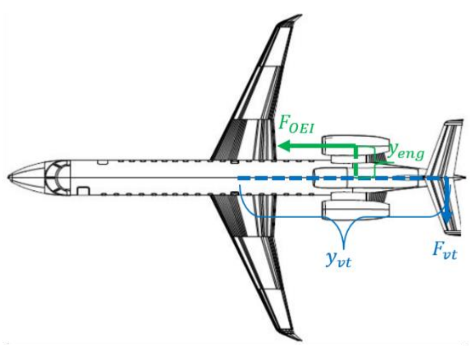

Figure 6: One Engine Inoperative condition

Eq. 14 to Eq. 18 shows the equilibrium equation for momentum and how to estimate vertical tail size of the trijet knowing the vertical tail size of the twin-jet and the installed thrust reduction.

$$\sum M = 0 \tag{14}$$

$$F_{OEI} \cdot y_{eng} = F_{vt} \cdot y_{vt} \tag{15}$$

$$q \cdot C_{L_{VT}} \cdot A_{vt_{twin}} = \frac{T_{total_{twin}}}{2} \cdot y_{vt} \tag{16}$$

$$q \cdot C_{L_{VT}} \cdot A_{vt_{tri}} = \frac{T_{total_{twin}}}{3} \cdot (1 - t_{r\%}) \cdot y_{vt} \tag{17}$$

$$A_{vt_{tri}}=A_{vt_{twin}}*\frac{2}{3}*(1\text{-}t_{r\%}) \quad (18)$$

The vertical tail area will affect the skin friction, this first result shows that trijet might have a smaller vertical tail area of around 60.4% of the baseline twin-jet.

3.6. Parasitic drag

The parasitic drag was determined using class II methods [6] [7] and a preliminary result, considering 9.4 % thrust reduction is shown in Fig. 7. Despite having less friction drag due to a smaller vertical tail, the trijet configuration has an increase of 3 drag counts when compared with the twin-jet used as baseline because of the addition of a third nacelle. Eq. 19 to Eq. 21 show the basic procedure to estimate the drag coefficient, the product IF.FF was assumed 1.5 for the nacelles[7].

$$C_{f_{turbulent}}=\frac{0.455}{(logRe)^{2.58}(1+M^2)^{0.65}} \quad (18)$$

$$C_{f_{laminar}}=\frac{1.328}{Re^{0.5}} \quad (19)$$

$$C_d=\frac{IF.FF.C_f.S_{wet}}{S_{ref}} \quad (20)$$

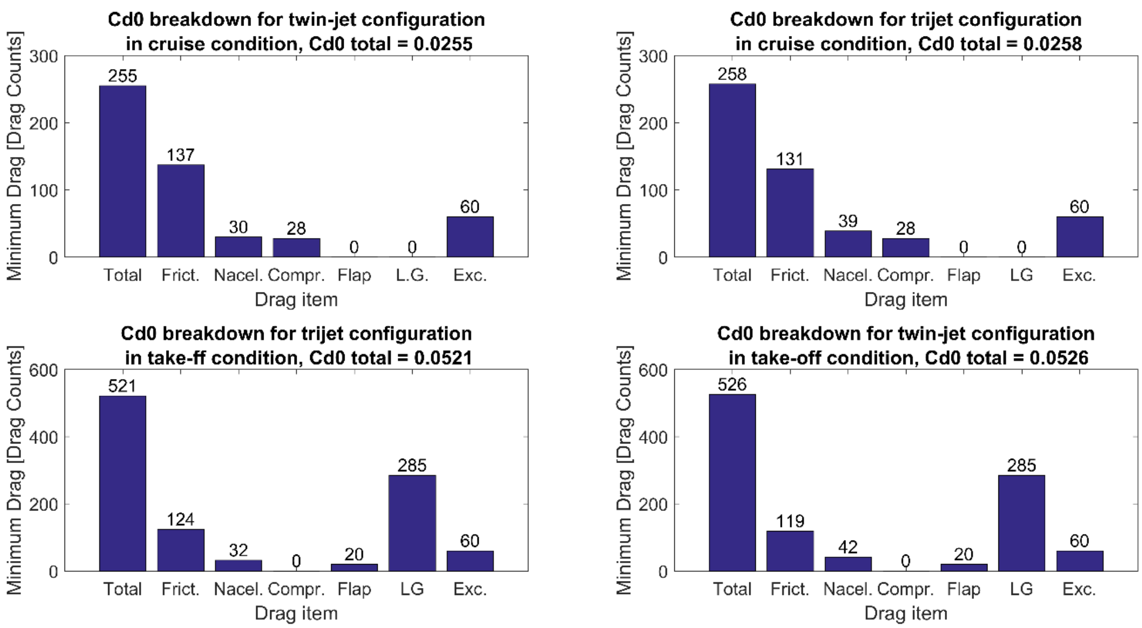

Figure 7: Parasitic Drag for twin-jet and trijet

4 CONCLUSIONS

The results show that the trijet configuration might lead to a lower thrust to weight ratio when compared to the twin-jet design when the balanced field length is the critical constraint, as showed in Table 5. In addition, aircraft with three engines might require a small vertical tail area due to less asymmetric momentum when one engine is inoperative. The methodology presented shows a slightly increase in weight and drag due to the addition of a third engine and nacelle. Furthermore, there is an increase of the flyover noise, since a lower thrust to weight ratio deteriorates the climb trajectory.

Table 5 – Main preliminary results.

Baseline Twin-jet	Baseline Trijet
Baseline Thrust: 100%	Thrust reduction for required BFL: $t_{r\%}$=9.4%
	Thrust reduction for FAR minimum climb gradient: $t_{r\%}$=22.3%
Baseline Vertical Tail Area: 100%	Vertical Tail Area: 60.4% ($t_{r\%}$=9.4%)
Flyover noise: 88.2 dB	Flyover noise: 89.4 db
MTOW = 48,500 lb	MTOW = 49,220 lb (1.6% increase)

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